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MISSION OPERATIONS AND DATA SYSTEMS DIRECTORATE

Renaissance Study of Spacecraft Integration and Test Systems

Final

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National Aeronautics and
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Abstract

This report describes the results of a study of spacecraft integration and test (I&T) conducted by the Renaissance Team. The study was started in October, 1995, and was completed in January, 1996. This report presents an overview of the phases of spacecraft I&T, the results of a survey of five ground data systems that supported spacecraft I&T, a list of requirements necessary for a GDS to adequately support spacecraft I&T. The report recommends subjects for future studies.

Executive Summary

Although spacecraft I&T and mission operations have historically been performed by separate GSFC directorates, the GDSs that support these activities have many functions in common. Declining mission budgets have prompted GSFC to use one GDS to support both spacecraft I&T and mission operations. In order to remain competitive in the GDS marketplace, the MO&DSD must meet the challenge of delivering GDSs which will support spacecraft I&T and mission operations. (Science operations was not part of this study.)

This study documents the practices and needs of the spacecraft I&T community. Renaissance will use this information to extend their second generation architecture and select COTS products for their GDS prototype which demonstrate spacecraft I&T capabilities. For this study Renaissance talked to representatives from: the ITOCC system used on ACE, the Epoch2000 system used on NEAR, the ASIST used on TRMM, the STOS used on SAMPEX, and the COMET system used on Clemintine. While each organization responsible for these systems has plans to deliver systems which will support both spacecraft I&T and operations, the Naval Research Lab's (NRL's) COMET is the most mature. NRL has been using the same GDS for spacecraft I&T and operations for approximately 20 years. NRL's development contractor, Software Technology Incorporated, successfully marketed an extended version of COMET (O/S COMET) as a generic command and control system. O/S COMET was selected by Motorola's Iridium project, which will have a constellation of over 60 satellites.

Section 2 of this study presents characteristics of GDSs which have one implication for the spacecraft I&T environment and another for operations. These characteristics include, for example, command loads, spacecraft contacts, manual intervention, configuration management, limit checking, and expertise of personnel. Section 2 also describes the different phases of spacecraft I&T from bench testing to environmental testing. With the exception of Clemintine the missions in this survey did not use their spacecraft I&T system in the early testing phases.

Section 3 contains the descriptions, perspectives and opinions from the survey participants about their I&T system. In section 4 the authors of this study make conclusions on: essential requirements for spacecraft I&T, a spacecraft I&T wish list, and external factors which influence the selection of I&T systems.

This study concludes that, as with operational GDSs, when it comes to spacecraft I&T one size does not fit all. Therefore development cost constraints need be an agreed upon as a percentage of the overall mission development budget. Now that one core system will be used to support spacecraft I&T and operations, flexible configurations will be needed to support users who are at different phases of the mission life cycle. A GDS might vary, for example, from a minmally configured PC for a bench tester to a network of workstations configured to support launch or lights out operations.

Table of Contents

LIST OF FIGURES

List of Tables

1.1

1. Introduction

1.1 Purpose

This study was undertaken to understand and document the needs of the spacecraft I&T community. A follow-on prototype task will evaluate currently available COTS products to see if they adequately address the needs of the spacecraft I&T community. This study does not identify the requirements of a ground data systems (GDS) that supports both operations and I&T. The authors recommend that the development of such a list be the subject of a follow-on study.

1.2 Background

Goddard Space Flight Center's (GSFC) Mission Operations and Data Sciences Directorate (MO&DSD) (Code 500) has traditionally built and operated the ground data systems (GDS) that control earth-orbiting spacecraft during the post-launch (or "operations") phase of a mission. MO&DSD systems and personnel have not traditionally supported spacecraft integration and test (I&T), the phase of a mission when the separate subsystems are combined to create a working spacecraft. Spacecraft I&T has been within the charter of GSFC's Engineering Directorate (Code 700).

Although spacecraft I&T and operations have been accomplished by separate GSFC directorates, the GDSs that support these activities have many functions in common. Both GDSs support the ground personnel's interaction with the spacecraft providing the basic telemetry monitoring and commanding capabilities needed to control the spacecraft. Over the years, Code 500 and Code 700 developed their own legacy systems to support their respective activities.

Declining mission budgets have prompted many of MO&DSD's customers to find ways to reduce the costs for deploying and operating a spacecraft. As a result, the costs inherent in procuring separate, functionally redundant GDSs for spacecraft I&T and operations has come under scrutiny. Some of MO&DSD's customers have begun to procure a single GDS to support both spacecraft I&T and operations. (This is becoming widespread at GSFC and throughout industry.)

In order to remain competitive in the GDS marketplace, MO&DSD's operational GDSs must be extended to support I&T. A number of recent MO&DSD activities reflect the directorate's interest in producing new configurations of legacy components that combine the functions of spacecraft I&T and operations. Examples include:

- Code 730 and MO&DSD working together to extend the ASIST I&T system with MO&DSD-developed legacy necessary to operations for use on MIDEX.
- Code 740 and MO&DSD working together to extend the STOS I&T system with MO&DSD-developed legacy necessary to operations for use of SMEX.

- MO&DSD working with the Applied Physics Laboratory to create the ACE Integrated Operations Control Center (ITOCC) which extends the Code 510 TPOCC operational system to perform the I&T function.

As part of the search for new systems that support both spacecraft I&T and operations, the Renaissance task is exploring the viability of a COTS solution (with possible integration with legacy components), such as Software Technology Incorporated's OS/COMET.

1.3 Approach

This study has attempted to accomplish these goals through the following activities:

- Survey the methods and tools used for I&T at GSFC (Codes 730, 740, and 500) and industry (Epoch 2000 and OS/COMET) and evaluate the strengths and weaknesses of each approach.
- Understand the factors that effect the selection of an I&T system.
- Provide a common definition of the steps I&T encompasses for satellite developers across GSFC and industry.
- Describe the capabilities a GDS must provide to qualify as an I&T GDS. A follow-on Renaissance prototyping effort will attempt to demonstrate that a COTS system can be used for I&T.
- Advise the Renaissance Second Generation architects of the needs of the I&T community.

1.4 Document Organization

This report is organized into the following sections:

- Section 1 describes the purpose of this study and the structure and contents of the sections of this document.
- Section 2 also contrasts some of the similarities and differences between spacecraft I&T and operations and provides a detailed description of the different activities that comprise spacecraft I&T.
- Sections 3 contains the results of our survey of I&T systems across GSFC and industry. Included in Section 2 are the perspectives and opinions of the survey participants. This section is not intended to be a detailed study of the capabilities of the systems surveyed.
- Section 4 presents our analysis of the requirements of an I&T GDS. The requirements described in Section 4 will provide the criteria for evaluating which COTS products can support I&T. Section 4 will also recommend areas for further study.

1.5 Survey Participants

The following people participated in this study:

- Elliot Rodberg (APL), the lead integrator for the Advanced Composition Explorer (ACE) being developed for NASA by the Applied Physics Lab (APL) in Laurel, MD. The ACE development team is using the TPOCC-based Integration and Test Operations Control Center (ITOCC) for I&T and the TPOCC-based Mission Operations Center (MOC) for operations.
- Jim Thompson (APL), the Lead Ground Systems Support Engineer for NEAR, a satellite also under development by APL. The NEAR mission is using Epoch2000 from ISI, Inc. for both I&T and operations.
- Leo McConville (ATSC), Test Conductor for the Tropical Rainfall Measurement Mission (TRMM). The TRMM spacecraft is currently being integrated using the GSFC Code 730-developed ASIST I&T system. TRMM will use TPOCC for operations.
- Dave Welch and Chris Hoffmann (ATSC), Instrument Team Lead for SAMPEX and Test Conductor for SWAS respectively. SAMPEX and SWAS are SMEX missions that use the GSFC Code 740-developed STOS system for I&T and the TPOCC for operations.
- Dave Schriftman (Naval Research Laboratory) was the mission lead for a series of spacecraft that developed and used the OS/COMET system. Developed by Software Technologies Incorporated (STI) for the NRL, OS/COMET has been selected for use in developing the ground data system for Motorola's Iridium program.

2.

2. Overview of Spacecraft Integration and Test

2.1 Comparison of Spacecraft I&T and Operations

Table 1-1 contrasts the differences between spacecraft I&T and operations.

Table 1-1. Contrast of I&T and Operations

Characteristic	Spacecraft I&T GDS	Operations GDS	Implications
Contact with Spacecraft	In real-time contact with the spacecraft during user-selected times and for user-selected duration.	In periodic realtime contact with the spacecraft as defined by the orbit of the spacecraft.	There is usually no impact if the I&T GDS fails to initialize properly during environmental tests. Because operational GDSs have traditionally been brought up for every pass, the operational GDS must reliably come up to support an operational pass. Operational GDSs must provide adequate processing for orbit and attitude to acquire the spacecraft for communications with the ground.
Command Loads	Develop one or two command loads which are used repeatedly.	Constantly create new command loads	Development of a robust command load system can be cost effective for an operational GDS but probably isn't necessary for an I&T GDS.
Manual Intervention	I&T is a labor-intensive activity requiring regular interaction by testers with spacecraft hardware.	Operations is generally routine and can be automated. Operations team cannot access spacecraft hardware.	Limited opportunity for automating I&T. Automation, to the extent it's possible, is achieved by STOL procedures. Testers must remain close to the actual hardware.
Configuration Management	Constant modification to the flight software and project database (PDB).	Updates to the flight software and PDB are infrequent and tightly controlled.	I&T systems must support rapid reconfiguration. Operational systems must prevent unauthorized or unintended updates from being uploaded.
Mobility of System	I&T system moves to different sites to support testing.	Control Center and/or Science Operations Centers are rarely moved.	I&T systems must be mobile enough to be move to support testing at multiple locations.

Limit Checking	Must allow testing of out-of-limit conditions.	Must prevent commands with out-of-limit parameters from reaching the space craft.	I&T GDSs must allow testers to override out-of-limit (OOL) safeguards, usually through bit-level commanding. GSE provides override switches that can protect spacecraft systems from damage during testing.
Expertise of Personnel	Detailed, bit-level knowledge of the performance envelop of spacecraft subsystems.	Overall knowledge of spacecraft operations and spacecraft performance.	I&T systems must provide bit-level access to commands and telemetry values.
Science Data Processing	Known results generated from scripted stimulus of science instruments by GSE.	Large volumes of science data from actual science instrument observations.	Investigators require an adequate set of science data analysis tools while most I&T science data processing can be performed in GSE.
Environment	Tightly controlled through GSE and environmental test chambers.	Space environment can not be controlled.	Conditions in operations are cyclic. Systems tend to degrade over time in operations, necessitating use of trend analysis.
Ground Support Equipment	Used to control environmental factors and simulate operational conditions	None.	I&T systems must allow control of GSE.
Interaction Between Users	Users are separated into independent subsystem teams.	Operations teams are co-located.	I&T GDS must provide mechanism to control commanding while allowing independent reduction and data analysis. I&T community wants only the data for the subsystem (box) of interest.
Level of Diagnostics	Testers are interested in board-level tests and patches	Operations is concerned with box-level diagnostics. Board-level fixes cannot be made during operations	I&T requires a robust set of low-level diagnostics

2.2 Role of Ground Support Equipment

One of the important differences between an operational and spacecraft I&T configuration is the use of ground support equipment (GSE) during the I&T phase. GSE is a broadly defined term that refers to any equipment used to support integration and test that is not part of the operational configuration. For the purposes of this study, GSE is more narrowly defined as computer hardware and software that simulates all or part of the spacecraft or the spacecraft's environment during I&T. Figure 2-1 shows the GSE used in the ACE I&T system.

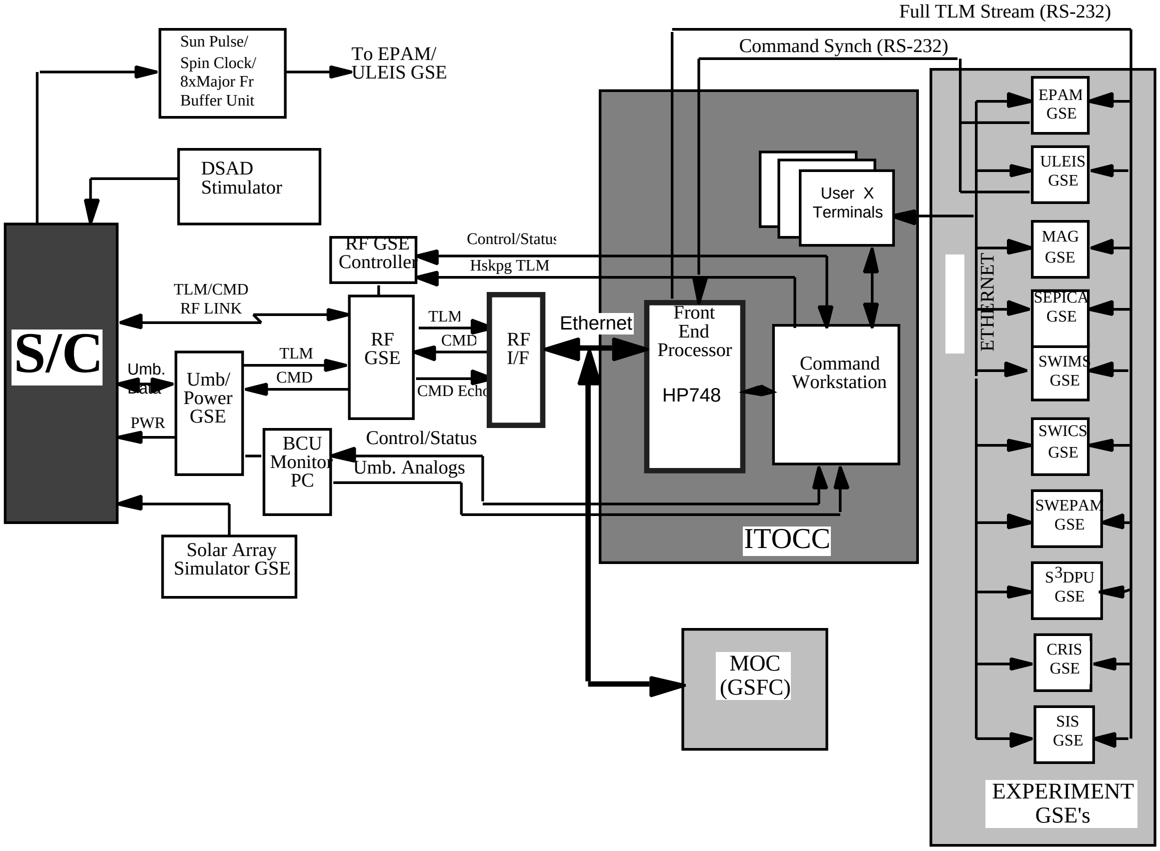

Figure 2-1 GSE for the ACE I&T Configuration

Functions of the GSE used during I&T include:

- Umbilical Power GSE - Provides power to the S/C through a pin connection, simulating the output of solar arrays. Later used for pre-launch checkout of the S/C and science instruments on the launch pad. The power GSE often includes a single emergency switch for turning off all power to the spacecraft.
- RF GSE - Simulates communication with the S/C using RF. As shown in Figure 2-1, the RF GSE sits between the spacecraft and ground system and simulates the radio frequency ground-to-space connection.
- Battery GSE - Simulates the batteries during I&T, allowing a more realistic simulation of the power management.
- Baseband GSE - allows commanding of the S/C directly, without an RF link.

This equipment is used throughout I&T. Each GSE box has it's unique APIs and manual interfaces. Ideally, commands to control GSE can be easily integrated into the test procedures that control the I&T scenario.

2.3 I&T Phases

Figure 2-2 depicts the progression of phases of the development, spacecraft integration and environmental test process which is generally followed by all missions. These phases are general phases and do not necessarily reflect the steps of a particular mission.

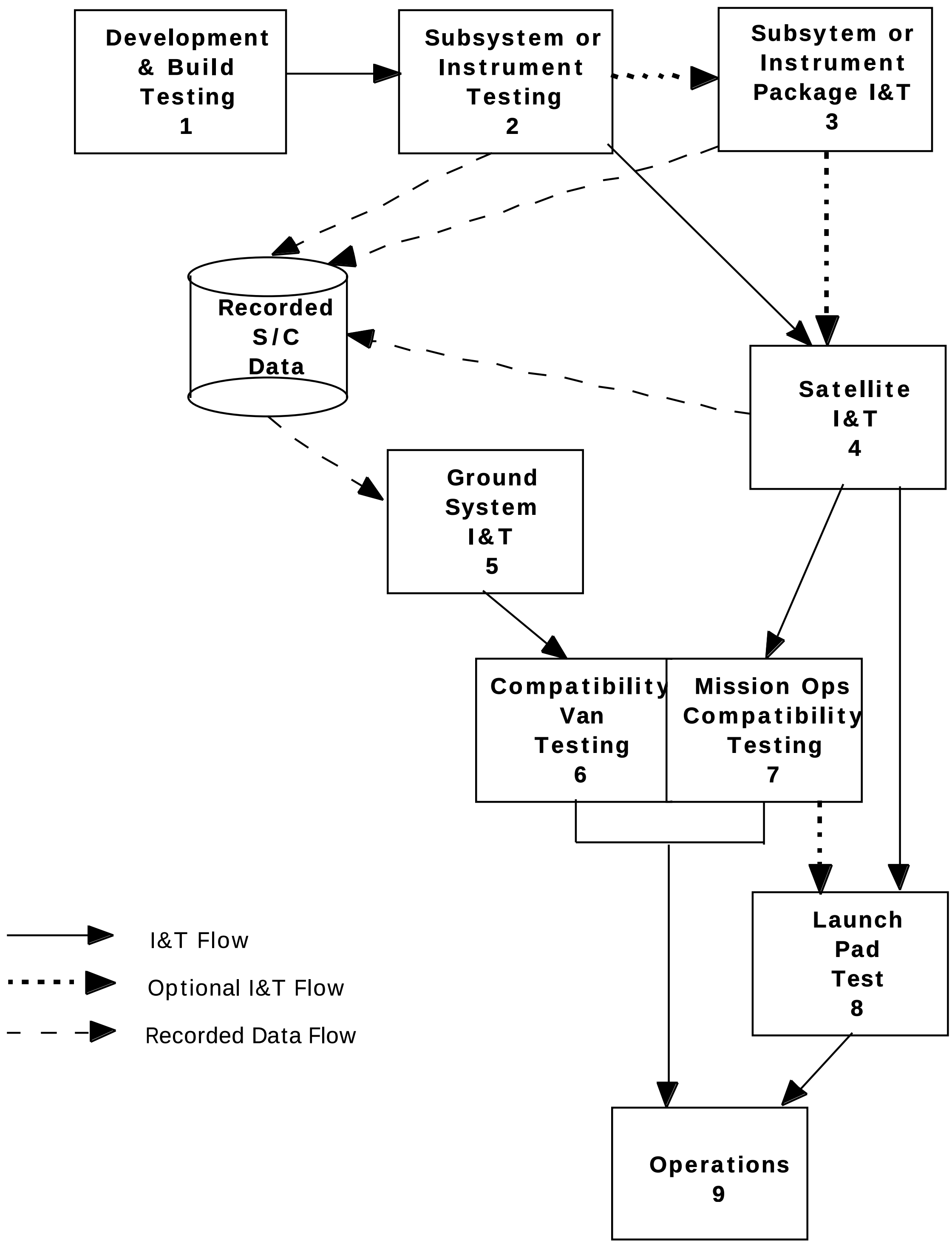

Figure 2-2 Phases of I&T

These phases are described in the following sections.

2.3.1 Development and Build Testing

This phase involves the subsystem or instrument "bread board" and component level development "bench" testing. (It is so called because it verifies requirements, sets benchmarks for later testing and can usually be run right on the developer's workbench. This term is also used during later "box level" testing since it can generally also be done on a workbench provided by a testing facility operator rather than requiring special facility provided handling equipment, other than for cleanliness.) During this phase, the instrument or subsystem design is verified and modified as necessary. The design of the boards and other hardware components can be verified as meeting specifications prior to assembling the "box" for subsequent functional and environmental verification. This phase also involves the development and checkout of the flight software. Multiple iterations may be done with the development and checkout of prototypes or Engineering Test Units (ETU's) and some interface testing with other box development groups may also be accomplished during this phase.

2.3.2 Subsystem or Instrument Assembly and Testing

Once the "board" level operation has been verified, the subsystem or instrument builder will now be ready to assemble (or integrate) the "box" (as the subsystem/instrument is often generically called) and begin to verify it's functionality, both in ambient conditions and under orbital environmental simulations. This testing is required to satisfy the project's Spacecraft Level Requirements as defined in the "GSFC General Environmental Verification Specification (GEVS) for STS and ELV Payloads, Subsystems and Components (GEVS-SE)".

2.3.3 Subsystem or Instrument Package I&T (optional)

This phase, if included in the satellite development plan, consists of putting some of the spacecraft subsystems or instruments together into an integrated package, and verifying that the integrated package is fully functional. This phase might also provide some environmental testing as needed to satisfy the GEVS requirements. This phase could involve the integration of numerous attitude control components and subsystems into an integrated attitude control package, the integration of numerous instruments and possibly a shared data processing unit onto a shared platform, the complete integration of the satellite bus prior to delivery and integration of the instruments, or the complete integration of the satellite payload (or instrument contingent) prior to delivery for integration to the satellite bus. (The use of the term payload in this context means the instrument segment. During integration and test with the launch vehicle, as well as the launch phase itself, the term payload is often used to refer to the entire satellite, which is in turn the payload for the launch vehicle just as the instrument package is the "payload" for the satellite bus.)

2.3.4 Satellite Integration and Test

This phase breaks down into many "sub-phases" and, depending on the amount of “prior” integration and testing done, could last anywhere from a few months to a couple of years or more.

2.3.4.1 Subsystem Delivery

The first sub-phase includes the delivery of the flight subsystems and the instrument(s) or payload, and the assembly of the spacecraft. Prior to assembly, each subsystem will undergo an initial bench test and checkout in order to verify that the box was not damaged during shipment.

2.3.4.2 Satellite Assembly

The assembly consists of both mechanical and electrical integration and checkout, box by box, as well as verification of software interfaces and electrical performance functional testing, including an aliveness test, a short and long form, or comprehensive, functional test, and diagnostic testing as needed to verify standalone performance after integration to the spacecraft. These checkouts are generally run from paper procedures, with each command entered by keyboard so that they can be synchronized with ground support equipment such as oscilloscopes, volt/amp meters, break out box reconfigurations and recording devices such as strip charts or cameras in order to verify the electrical command signal before, during and after integration. Also, any required mechanical interface work which is needed, will be performed during this sub-phase. This may include such things as an interface fit check, a tolerance build-up check or any optical or mechanical critical alignments which are necessary. Generally most interface troubleshooting will occur during this phase, particularly of the local interfaces to the current “box” being integrated. This checkout usually also includes (but this could conceivably be done earlier with proper support) the development and verification of the command and telemetry database and of the functional test procedures for use during the environmental testing phase. Procedure checkout consists of developing a test plan, writing test procedures (often in STOL), use of a syntax checker (if using a scripting language), and review of the procedures by the subsystem or instrument team. Then these procedures are generally run “live” with the cognizant lead present (usually after many iterative reviews).

2.3.4.3 Environmental Testing

Once the spacecraft has been assembled and the functionality of each subsystem has been validated, the system is ready for the environmental testing. Generally a pre-environmental spacecraft checkout and characterization comprehensive test is run, both to establish a baseline against which to measure future performance, and also as a benchmark to show readiness to begin environmental testing.

These environmental tests are completed to satisfy the projects spacecraft level requirements, to show compliance with the launch vehicle requirements and to prove launch readiness. During this period, select pre- and post-test evaluations and unique functional checkouts will be performed as needed and appropriate. These tests include:

- EMI/EMC (electromagnetic interference/compatibility) testing to verify the payload can operate properly in the electromagnetic environment expected at the launch site, during the launch phase and during the on-orbit operational phase of the mission. These tests include radiated susceptibility, radiated emissions, conducted emissions, conducted susceptibility and radiated emissions survey. These test will be run with the spacecraft in both launch mode configuration and in select on-orbit modes such as safe hold and normal mode, as required.

- Weight, Mass Properties and Spin Balance checkout to verify such spacecraft properties as the weight, the center of gravity and the moment of inertia of the spacecraft. Typically these checkouts are done with the spacecraft in a powered down mode.

- Vibration testing which may include 3-axis random vibration, 3-axis sine burst and 3-axis mechanical shock testing (basically shaking the spacecraft). Mechanical shock testing may test self-induced shock, as exhibited by a pyro firing, or external shock, such as being carried in a rocket launch, as necessary. This testing is generally run with the spacecraft in it's launch and early orbit mode(s) configuration and may include running an Aliveness Test between each axis (x, y, z) test in order to detect gross failures, and select functional checkouts before and after in order to detect any more subtle failures due to the stress imposed by this testing. Alignment checks, particularly, may be required after vibration testing to ensure the spacecraft launch will not effect a sensitive instrument alignment.

- Thermal Vacuum and Thermal Balance testing is performed to demonstrate both operational and mechanical functionality at the temperature extremes which might be experienced by the spacecraft. The thermal balance is performed in order to obtain a thermal profile of the spacecraft and to validate any previous thermal modeling. During thermal vacuum testing, the spacecraft is subjected to hot and cold thermal cycles under vacuum conditions. Spacecraft performance is demonstrated at each temperature plateau (hot and cold soaks), after any scheduled survival (extreme heat and/or cold which might be caused by an anomaly during launch, maneuvers or during attitude control functions) soaks and during temperature transitions. During this testing, there is a need for special limit and state definitions (different from the ambient definitions used during the rest of the I&T phase) and this testing presents a good opportunity for verification of the on-orbit limit and state definitions. Many special tests, such as mechanical deployments, leak tests, end-to-end ground system checkout and spacecraft operational testing, are also performed during this opportunity.

- Acoustic testing to verify the payload can operate properly in the acoustic environment expected at the launch site, during the launch phase and during the on-orbit operational phase of the mission. Select functional checkouts are generally run before and after this testing.

- Magnetic Properties and Magnetic Calibration testing done in order to characterize the inherent magnetic properties of the vehicle. Typical testing done includes functional testing in various spacecraft mode configurations (such as normal or safe hold), a spacecraft deperm, measurement of the spacecraft residual dipole moment, and attitude monitor and control system testing which includes such items as magnetometer contamination testing, B-dot trim, B-dot closed loop response testing, B-dot phasing testing and sun precession testing.

- Special Functional Testing to include orbit scenario tests in order to characterize the battery charge/discharge cycle profile in all functional modes and utilizing GSE such as a solar array simulator. This testing might include characterizing profiles for end of night simulations (with power supplied by the spacecraft batteries only, at the minimum spacecraft bus voltage), early morning simulations (where the maximum charging occurs), end of day simulations (when the batteries are trickle charging) and early night simulations (with power supplied by the batteries only, at maximum spacecraft bus voltage). Other types of special functional testing include interference testing, leak tests, calibrations, mechanical function tests, source tests, quiet mode or background monitor tests, high voltage operational testing, software status, verification and patch capability testing, RF testing (reception, broadcast, ranging), clock maintenance, telemetry verification (all rates and types - recorded vs. real-time), watchdogs, time-outs, errors and resets verification, stored command execution and on-board control and overrides checkout.
- Generally a post-environmental spacecraft checkout and characterization comprehensive test is run in order to monitor for any degradation which may have occurred during the environmental test phase, as compared to the pre-environmental baseline comprehensive test. Alignments may have to be rechecked and/or readjusted during or after the environmental test phase.

2.3.5 Ground System Integration and Test

This phase consists of development and build testing, and testing to insure that the design meets all requirements prior to delivery of a control center component to the integration organization Ground System I&T also includes acceptance and operational testing performed by the integration organization to verify functional requirements. Ground system I&T is where all the system components are integrated together to form a ground system. Such system components include the attitude control system, the ground antenna, and other components such as the network.

2.3.6 Mission Operations Compatibility Testing

This phase consists of compatibility and external interface checkout between all of the remote and local ground system support sites, including the MOC, SOC, FDF and the ground and/or space networks. This includes both external communications and local ground systems interfaces.

2.3.7 Compatibility Van Testing

This phase consists of verification of compatibility between the spacecraft and the space and/or ground network stations which will provide on-orbit support. This includes verification of both uplink and downlink frequency, modulation and ranging requirements.

2.3.8 **Launch Site Testing**

Launch site testing includes the shipment of the spacecraft to the launch site, initial checkout of the spacecraft upon arrival, last-minute interface and operational verification, integration of the spacecraft (payload) with the launch vehicle, launch vehicle and payload checkout to verify interfaces and separation sequences, and launch countdown, liftoff and separation sequences.

2.3.9 **Operations**

Launch support, verification of the spacecraft during early orbit, starting with the initial acquisition contact, on-orbit spacecraft checkout, instrument checkout and calibration, transition to normal operations, normal operations and the performance of any special operations, including maneuvers, calibrations and special science operations and windows of opportunities, and contingency operations, including flight software maintenance, anomalies and failure mode recoveries.

3.

3. Survey of I&T Systems

NOTE

The following sections contain the responses and opinions of the survey participants. Their views are based on their own experience performing I&T. The following sections are not intended to be a comprehensive survey of the capabilities of the systems used by these participants.

3.1 Integration and Test Operations Control Center (ITOCC)

3.1.1 Description and Background of I&T System

Throughout the 70s and 80s, I&T systems at APL have evolved incrementally from the instrument ground support equipment (IGSE). After I&T, the satellite was turned over to a separate organization for operations. The Operations organization usually developed their own ground data system (GDS). During the 1990s, APL has moved towards the use of the operational system during I&T.

We interviewed Elliott Rodberg (APL) in Building 1, Room B-10 at the GSFC on October 12, 1995.

3.1.1.1 I&T System Architecture

Figure 3-1 depicts the high level architecture of the ITOCC configuration.

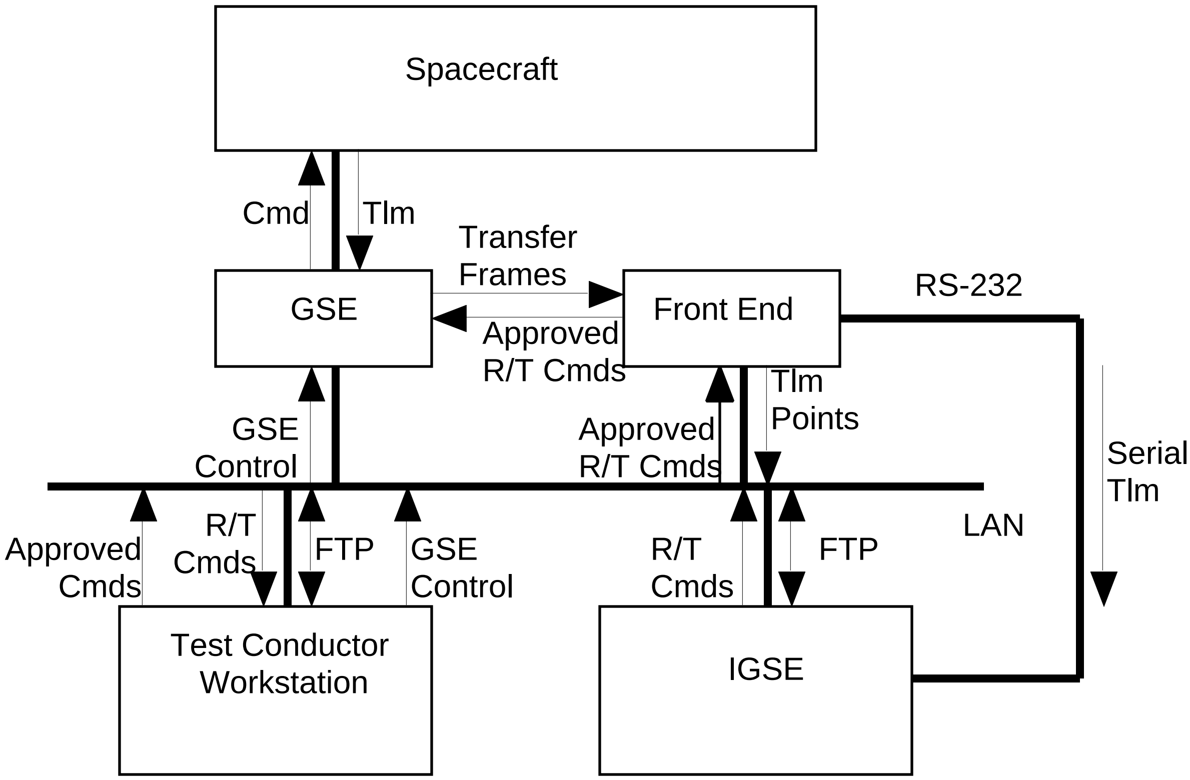

Figure 3-1 ITOCC Architecture Diagram

3.1.2 **Alternatives Considered to Selected Approach**

Two alternatives to TPOCC were considered for the ACE I&T system - a VAX-based workstation based on an APL legacy system, and a COTS PC-based system. APL paid for the I&T-unique elements of the ITOCC - a relatively small piece of the total system. In the case of ACE, the cost of extending the operational system to perform I&T was about the same cost as developing their own I&T system. Although the costs are even, the advantage of a smooth transition from I&T to operations was a major factor in choosing the approach.

3.1.3 **System Use in I&T Phases**

The ITOCC was used for subsystem I&T (Figure 1-1, Step 2). The subsystem and instrument teams did not want to use ITOCC during bench testing because the UNIX environment was considered too complicated. Instead, the subsystem and instrument teams used their PC-based GSE during bench testing.

The benefits of using a more full-featured system such as ITOCC are maximized when it is was used beginning with bench testing. However, the instrument and subsystem teams tend to want tight control over their environment and prefer to use their own GSE.

3.1.4 **Perceived Strengths and Weaknesses of the ITOCC System**

Instrumenters could not control the GSE directly. Instrumenters had to request the test conductor to send a commands on their behalf.

All science data processing was performed by GSE. The ITOCC system did not provide any science data processing.

ITOCC does not allow testers to override command checking that would allow a tester to send erroneous commands to the spacecraft.

3.1.5 **Wish List for Changes to the Selected Approach**

The following is a wish list for how Elliott Rodberg thought the ACE ITOCC could better support I&T:

- user control to turn limit checking on and off by subsystem. Current capability allows user to control all checking or checking on a single telemetry item. (This capability has subsequently been implemented and delivered to the APL.)
- Have displays that contain alarms stay red until manually reset by the operator. Currently, when the alarm condition passes, the display is automatically reset. (This capability has subsequently been implemented and delivered to the APL.)
- Be able to send Science Instrument-specific telemetry to IGSE. Currently, all telemetry is sent to the IGSE.
- Time stamp event messages as they are created, not when they are received at the event subsystem. This will enhance the ability of testers to understand the sequence of events in a test.
- Provide an interface to the IGSE used to stimulate an SI. Currently, control of this IGSE is manual.
- Currently, instrumenters cannot directly control the spacecraft - they only monitor telemetry. Provide an interface to allow instrumenters to command the spacecraft through the MOC.
- At the user’s option, stop procedure execution when a telemetry item is out of limits. Currently, the procedure continues to execute. (This capability has subsequently been implemented and delivered to the APL.)
- Some way of comparing the spacecraft state after each command.

3.1.6 **GDS Functions Not Included in Test Configuration**

The ACE I&T is not required to test the following GDS functionality:

- Science Data Processing
- Scheduling

- Trending
- Any processing related to pass windows.

3.1.7 **Roles of Testing Personnel**

The are generally two roles associated with I&T:

- Test Conductor writes test procedures and controls the testing environment.
- Test Operator is needed to support the test conductor and monitor the IGSE.

3.1.8 **Role of Automation and Expert Systems**

Expert systems such as GenSAA have been considered for use in I&T, mostly to automate execution of test procedures.

3.1.9 **Staffing Level**

NOTE

> The staffing levels gathered for this report were not normalized across the various missions that participated in this survey. As a result, the figures cited cannot be used to estimate costs for developing and supporting the missions..

Staffing of I&T for ACE includes:

- 9 science instrument builders
- 8 for spacecraft I&T including subsystem engineering support
- 10 for satellite testing.

3.1.10 **Size and Maturity of the System**

Long time between releases means it's difficult to get requested enhancements implemented.

3.1.11 **Issues Related to the Transition to Operations**

Examples of things that a tester may wish to modify which would not normally be allowed in an operational system:

- Sync pattern
- Override patterns

3.1.12 **Modifications Necessary to Support New Missions**

Most changes related to supporting new missions are database to the project database to define:

- spacecraft housekeeping
- Instrument housekeeping
- Health & safety telemetry values
- Science data, as far as it affects health and safety.

3.1.13 Miscellaneous

TPOCC simulator required additional capabilities because the TPOCC Internal Simulator and TPOCC Advanced Spacecraft simulator (TASS) could not command or control the GSE, so the ACE I&T team is building a simulator that can.

When qualifying a S/C, an important consideration is the number of hours a subsystem has been used in I&T. I&T should take a sufficient amount of calendar time to allow testers to develop confidence in the subsystem. In other words, I&T establishes the functionality as well as the reliability of the subsystem

3.2 Spacecraft Test and Operations System (STOS)

3.2.1 Description and Background of I&T System

We interviewed Dave Welch of Allied Signal, Lead Instrument Engineer for SAMPEX, and Chris Hoffmann of Allied signal, Test Conductor for SWAS.

3.2.1.1 I&T System Architecture

Figure 3-2 depicts the high level architecture of the STOS configuration.

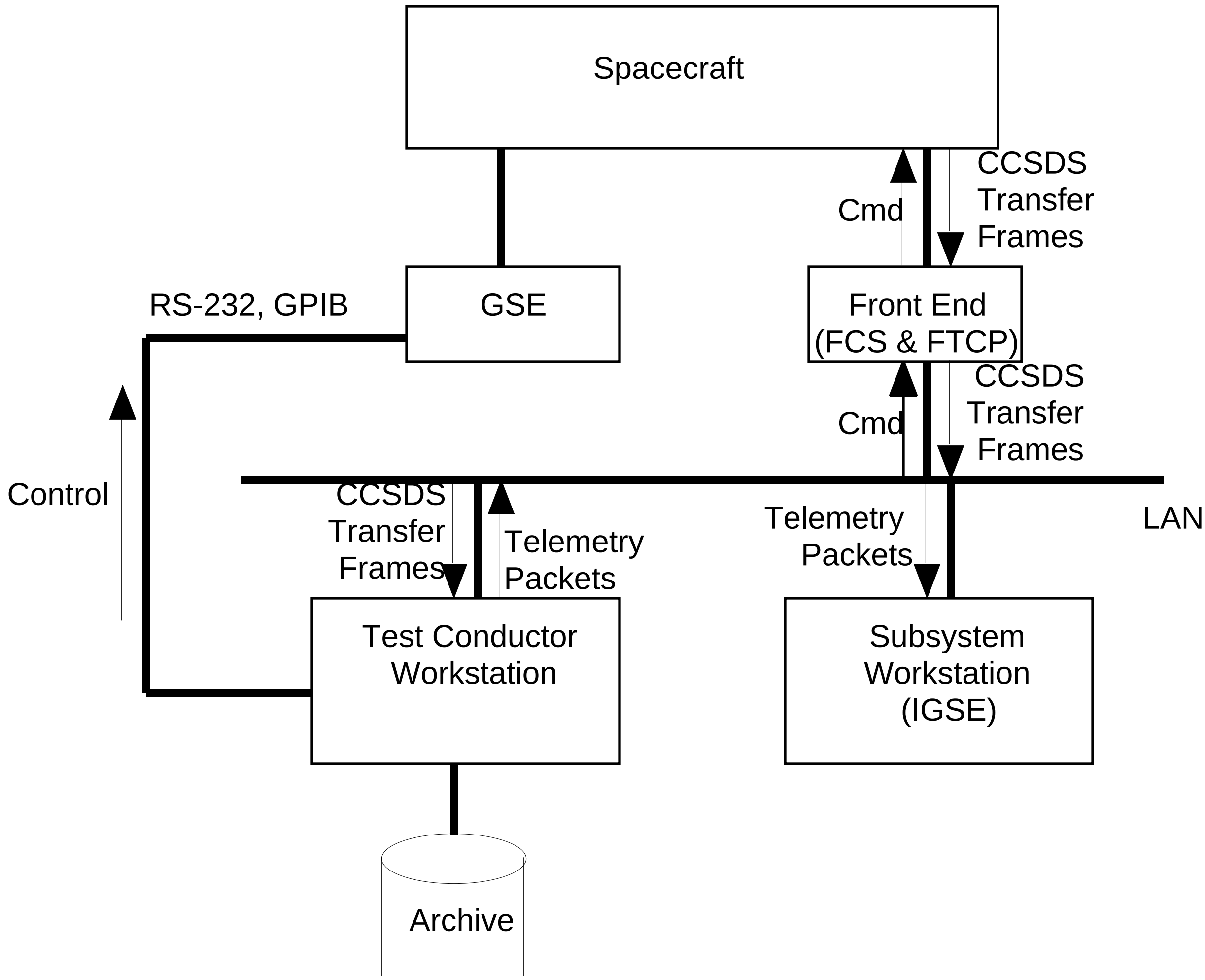

Figure 3-2 STOS Architecture Diagram

3.2.2 **Alternatives Considered to Selected Approach**

STOS was developed specifically for the SMEX series.

3.2.3 **System Use in I&T Phases**

Subsystem development teams used non-STOS PC-based GSE for bench testing. As described in Section 1, GSE provide telemetry and command processing and stimulate and simulate various spacecraft subsystems and their environment. Testers used STOS beginning with the subsystem integration phase. The integration of the separate data base modifications from the various teams into a single project database was a painful process.

3.2.4 **Perceived Strengths and Weaknesses of the Selected Approach**

Test Conductor Workstation (TCW) transformed science data from transfer frames to packets. The subsystem workstations expected packets. All science data had to go through the TCW for processing. This architecture meant that other tests could not be conducted while this data processing was taking place.

Control of GSE was limited to the manual interventions of testers. There was no command interface between the STOS and the GSE.

3.2.5 **Staffing Level**

NOTE

> The staffing levels gathered for this report were not normalized across the various missions that participated in this survey. As a result, the figures cited cannot be used to estimate costs for developing and supporting the missions.

There were between 50-60 people in SWAS I&T, with anywhere from 1-12 working at any one time. (There were generally about 25 people at the daily status briefing.) A typical subsystem I&T team is made up of about 8-10 people: a lead engineer (1), support specialists (2-3), an electrical specialist (1), mechanical specialist (1), a flight software specialist (1) and a lead and co-investigator (2). There were between 6 and 10 test conductors for SAMPEX.

SAMPEX integration took about 4 months and testing took 4 more months.

3.2.6 **Issues Related to the Transition to Operations**

For SWAS, the science instrument teams used the STOS test conductor workstation (TCW) during the bench tests. This meant that the PDB was checked out and all science instrument teams used the same database. Typically, each science instrument team develops their own PDB using their own platform (often a PC), and science instrument team's telemetry definitions must be reconciled with the official PDB - a time-consuming process. In general, the earlier the different teams begin using the same system, the greater the payoff in terms of cost and time savings.

Based on his personal experience in both operations and I&T, Dave Welch believes the following functionality needs to be added to the typical operational GDS such as TPOCC to support I&T:

- Add functionality to the subsystem workstations to process transfer frames of SD, not just packets. The rationale for this request is that otherwise the front end becomes a processing bottleneck.
- Add the capability for instruments to send a limited set of commands directly to the S/C. Currently, commands are sent only by the TCW. This capability needs to be managed carefully because the test environment needs to be carefully controlled in

order to correctly interpret test results. However, such a capability would allow parallel testing and more efficient allocation of test personnel's time.

- Provide a log of what commands were sent to the S/C, and precisely in what order. Currently, this is often provided by a line printer. Whether it's a printer or a screen, a tester should be able to review the log without interrupting any ongoing testing.
- Override the command monitoring function to send "bad" commands to the S/C. This is needed for testing anomalous conditions.
- The system must be easily transported. I&T moves from one site to another, often to take advantage of special equipment, such as is needed during the thermal/vacuum tests. I&T often requires manual intervention with the spacecraft or GSE hardware, which requires the I&T system to be collocated with the testers. In general, the subsystem experts need to be with the S/C. The more transportable the test system, the better and more useful for the testers. (That has been one of the drawbacks of the TPOCC architecture with the special hardware front end - it was not easily transported from one test site to another.)
- Dave felt there was need to easily access statistics and other debugging information about telemetry decom. Statistics should be included for raw packets, for example. (Currently, TPOCC requires a delog process to make these kinds of statistics available.)

Dave Welch believes he following functionality needs to be added to a typical I&T system such as STOS to make it useful operational systems:

- Command Load and Command Management systems, including maintenance of the ground reference image (GRI). In I&T, it's less critical for a command to leave the spacecraft in a state that may cause it harm. Dave gave the example of leaving an science instrument pointing at the sun while in stellar mode. Nothing bad is likely to happen in I&T but this could burn the science instrument if it happens operationally. Therefor, tractability of commands and detailed knowledge of the configuration of the spacecraft needs to be maintained in the operational system.
- Flight Software (FSW) Maintenance and Configuration Management (CM). During I&T, each instrument team is responsible for maintenance and enhancement of their own FSW. In operations, this must be closely monitored and coordinated.
- Data Analysis and Trending Capabilities are generally lacking in I&T systems. There is no central archive and trending function.
- Science Data Processing. This is generally handled by the IGSE, not by the I&T system itself (that is, the TCWS).
- Configuration Monitoring, Alarms, State Determination, and other "smarts". These features are generally shunned by I&T users because these users are the experts knowledgeable of their respective SIs down to the bit and byte level. (**N.B.** There is an important implication here in that generally speaking, an I&T-based system requires experts to use it - the antithesis of "lights out" operations. Testers tend to be experts on

the spacecraft and so generally have a position that less functionality is needed for the operational system.)

3.2.7 Unresolved Issues and Questions

Dave Welsh had the following specific concerns related to using COTS GDSs for I&T:

- Does the COTS GDS allow enough bit level control that a tester can override limit checks on commands?
- Is it flexible enough to allow you to try something once easily? On this point, Dave thought STOL was a bit restrictive.
- Testers often work in binary, especially in bench tests. Does the COTS package allow you to play at that level.

(Note that there is a comparison between STOS and the other Code 700 I&T system ASIST in the next section.)

3.3 ASIST

3.3.1 Description and Background of I&T System

TRMM is a low earth orbiter that is currently in electrical integration and test in Building 7 at GSFC. There were no unique requirements drivers for the TRMM mission.

We interviewed Leo McConville (Allied Signal), the TRMM I&T Test Conductor, in GSFC Building 5 on November 21 and 31, 1995. We interviewed Chris Hoffmann, Test Conductor for SWAS, at Greentech IV on December 19, 1995.

3.3.1.1 Architecture

The ASIST architecture is made up of the Front End Data System (FEDS) that performs frame sync, R/S decoding, and then distributes packets to the various workstations. The packets are extracted by the VME hardware and then passed to the FEDS. (See Figure 3-3). Workstations are either the test conductor workstation (TCW) or an associate workstation (ATCW).

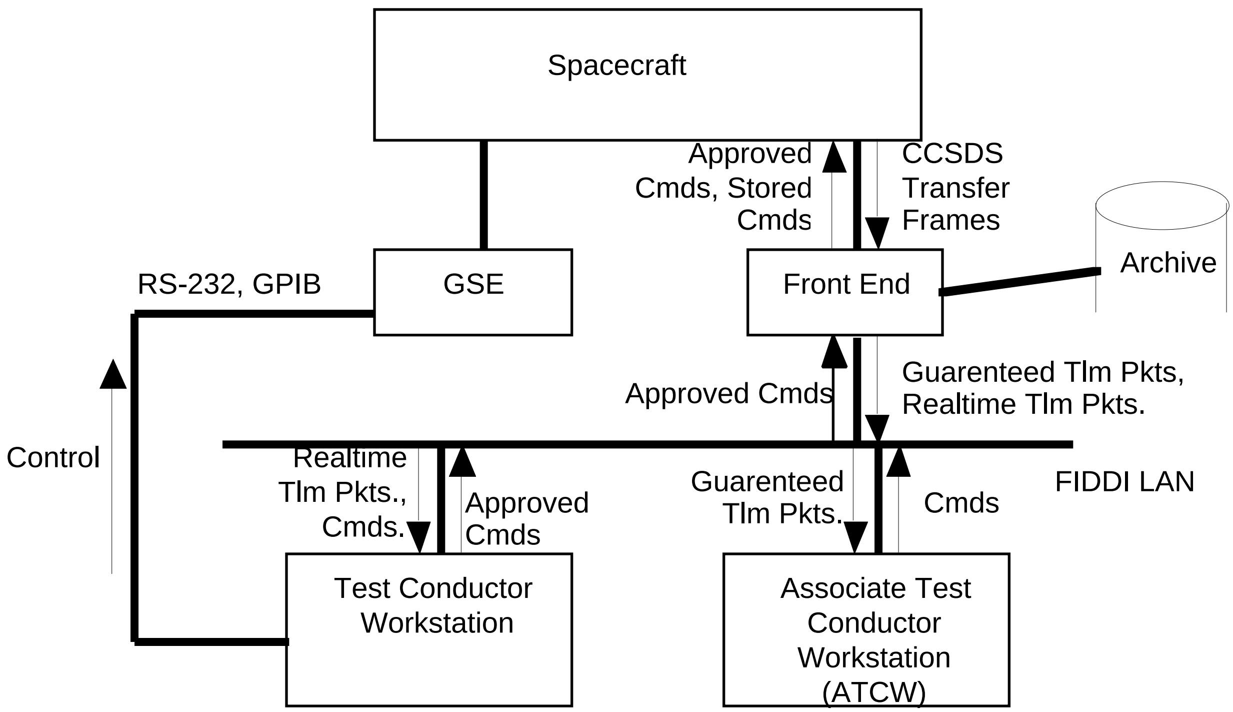

Figure 3-3 ASIST Architecture Diagram

3.3.1.2 **Ground Support Equipment**

The TRMM I&T configuration has the following GSE:

- Attitude Control System (ACS) GSE for simulating the space environment and stimulating the ACS sensors. The ACS GSE models the Earth and Sun.
- Electrical GSE controls and monitors the essential (spacecraft chassis) bus and non-essential (Science Instrument) bus. It provides an interface for the power subsystem specialist to control, monitor, and simulate current to the spacecraft. The umbilical connection to the spacecraft goes through this GSE.
- Battery GSE monitors cell voltage and temperatures, and simulates these telemetry values when necessary.

3.3.2 **Alternatives Considered to Selected Approach**

ASIST was selected for TRMM because it was successfully used on XTE, a mission with requirements very similar to TRMM.

3.3.3 **System Use in I&T Phases**

ASIST was used beginning with subsystem integration and test. Efforts to get the subsystem developers to use ASIST earlier did not work.

3.3.4 **Perceived Strengths and Weaknesses of the Selected Approach**

In the ASIST architecture, all commands are sent through the TCW, which must approve critical commands before they are sent to the S/C. ATCW can see all the commands being sent to the S/C. The FEDS has the ability to store a set of commands that can be sent to the Spacecraft is an emergency without using ASIST. The FEDS has the ability to store a set of commands that can be sent to the Spacecraft in an emergency without using ASIST. This capability is useful for emergency operations when the network prevents use commanding of the spacecraft.

ASIST allows users to enter commands in a hexadecimal format. The command string is displayed in hexadecimal, not using command mnemonics.

ASISTs limit alarms are turned off when the alarm condition passes - if the testers do not see the alarm message on the event s page, the alarm will be missed

Each ATCW has a distribution table that can be updated on the fly that determines which AP IDs are processed by that ATCW. This feature makes ASIST particularly flexible in changing the data received by a workstation.

The ASIST architecture is tied to CCSDS and may not work well for missions using another telemetry format.

The ASIST display builder allows the user to define new pages by copying the definition of an existing page and modifying the definitions. This feature makes it easy to define pages that are similar to one another.

In general, an impressive number of easy to use displays are available through ASIST. However, there is only one workspace for displaying all windows, which can result in a cluttered display.

ASIST has two possible routes for telemetry, depending on the needs of the tester. A workstation can connect either directly to the FEDS and receive the data in realtime, with the possibility of dropping packets, or to the Digital History Data Store (DHDS) which captures all packets, but can fall behind realtime by as much as 15-20 seconds.

ASIST allows the user to configure the database through the use of a Record Definition Language (RDL). The FEDS downloads the revised realtime files to each workstation in the configuration. The PDB can be changed and reconfigured in 10 minutes. (Most other systems require 2-3 hours to complete a modification to the DB). ASIST’s ability to rapidly reconfigure the database is outstanding.

The user interface to the playback and archive function is very easy to use. There is a 10 GB hard drive for archiving data. ASIST is sized to save every bit of data from I&T. Testers do not regularly playback a full recorder’s worth of data.

3.3.5 **Wish List for Changes to the Selected Approach**

Leo McConnville felt the following items would be useful extensions to the functionality of the ASIST system:

- Mnemonics for commands and command verifiers displayed on the workstations

- Multiple work spaces (as provided by HP View).
- Control GSE from the ASIST workstations. Although some commanding is currently done from the workstations, not all GSE functions are accessible from the workstation.
- Cross reference AP ID and mnemonics for the display builder.
- mnemonic builder
- support for a library of commonly used mnemonics.
- Expert knowledge is required to build up knowledge of the spacecraft for operations. Expert systems might be useful for maintaining the consistency between procedures and displays. (For example, if a tester changes the name of a telemetry mnemonic, an intelligent system could automatically update all procedures with the new name.

3.3.6 GDS Functions Not Included in Test Configuration

The ASIST I&T system does not test science data processing.

3.3.7 Roles of Testing Personnel

Test Conductor is in headset communication with all test personnel. There are 2 or 3 test conductors on each shift, one main test conductor and one assistant. (On SMEX there was a single test conductor.) There is one overall hardware expert, and specialists for each of the subsystems. Science instruments are incorporated along the way. (That is, SIs do not necessarily have to be integrated only after the spacecraft is completely integrated.)

3.3.8 Size and Maturity of the System

ASIST version 4.2 in currently in use on TRMM.

3.3.9 Issues Related to the Transition to Operations

Generally speaking there are many potential benefits to be gained from using a single system for both operations and I&T. For example, any of the engineers that support launch and early orbit are totally unfamiliar with the displays of the operational system. This lack of familiarity hampers troubleshooting during the critical lunch and early orbit phase of the mission. There is more confidence in a system that has been used all through I&T

3.3.10 Modifications Necessary to Support New Missions

ASIST presumes a mission will be using CCSDS. There could be additional costs to modify ASIST to operate for a mission that does not support the CCSDS.

3.3.11 Miscellaneous

Compared to ASIST, Leo McConnville felt the STOS (Code 740) offers fewer features to the integrators and testers:

- The STOS page editor makes it tedious to build new pages.
- Changes to the PDB are handled by the system administration organization, which must recompile and reload the ODB. This is a time-consuming process.
- Archive and playback uses Metrum tape. This is an inexpensive medium, but is not as reliable as disk and is time-consuming to playback because it is not a direct access medium.
- ASIST has extended STOL to allow variable substitution, foreign directives, and parameters. These features are important when STOL procedures are large. For example, the comprehensive evaluation test for TRMM is over 80 K lines of STOL.

3.4 Epoch 2000

3.4.1 Description and Background of I&T System

NEAR is a deep-space probe that is being built and operated by the Applied Physics Lab under contract with NASA. The NEAR Mission Operations Center will be located at APL. An important design driver for NEAR is that it is in contact with the Deep Space Network (DSN) for 8 hours per day. During this contact, the flight operations team must assess the condition of the spacecraft and make any adjustments that may be necessary. This requires the ground data system to be reliable and perform according to specifications.

The NEAR mission managers desired to have a single system for I&T and operations. NEAR is the first use of Epoch 2000 in an I&T environment.

We interviewed Jim Harrison, Lead Ground Support Systems Engineer, on November 28, 1995, in Building 5 at GSFC, about NEAR's approach to I&T.

3.4.2 Alternatives Considered to Selected Approach

NEAR mission management commissioned a trade study that evaluated 7 or 8 alternative combined I&T and operational ground data systems. Among the systems considered was TPOCC (proposed by CSC), a system from Martin-Marietta, and Epoch 2000 (ISI), which was finally selected. (Interestingly, many of the other systems were rejected because their user interfaces were **too** graphical for the I&T team. This highlights one of the reoccurring requirements of the test team - for a simple, text-based user interface.)

ISI, the builder of the Epoch 2000 system, was also a key subcontractor to CSC for the development of TPOCC. The two systems are similar in many respects. The key factor was cost - the Epoch 2000 solution was about half the cost of TPOCC.

3.4.3 System Use in I&T Phases

The Epoch 2000 system was used starting with Subsystem and Instrument I&T (Figure 1-1, Step 2). Jim Harrison said that there is a cultural bias against using anything other than PCs and Macs for Subsystem Bench Testing. This makes the transition from Bench Testing to Subsystem I&T

difficult because the database used by each subsystem development team must be reconciled with the mission project database.

3.4.4 Perceived Strengths and Weaknesses of the Selected Approach

NEAR has a CCSDS-compliant protocol for command syntax. The Epoch 2000 system did allow testers to enter illegal and out of range commands needed for testing. Database definitions of variable length commands that are not easily updated by the Epoch 2000 displays - approximately four displays need to be opened to enter or update a command definition and there was no shortcuts for entering the data. Epoch2000 did not provide a way to use an existing command definition to define a new command that is almost identical to it. This resulted in a lot of unnecessary and time consuming data entry. There are too many screens needed to update an existing command. Another perceived shortcoming of the Epoch 2000 commanding capability was that any workstation could send a command to the spacecraft, which did not provide the level of control necessary for I&T.

Epoch 2000 uses a current value table on the front end to serve telemetry values to other workstations. The original architecture called for the front end to perform telemetry decommutation in software. This approach caused performance problems, and a new architecture emerged that has the front end distributing packets, and the individual workstations perform the decom.

Epoch2000 did not provide the Level Zero processing of science data for NEAR.

It was easy for the I&T team to define new telemetry points using the Epoch2000 displays. A perceived shortcoming of the Epoch2000 system was the time needed to rebuild the project database. It took three hours is needed to reconfigure the Oracle database that contains the definition of the telemetry and command formats and produce the “flat files” that are used at runtime. There are constant changes made to the PDB during I&T, and this lag time is a major problem. (Ideally, this process should take 15 minutes or less.)

The Epoch2000 reports for looking at database settings are voluminous and therefore not particularly useful.

The Epoch 2000 system is very mobile. The NEAR I&T team took just one day to set when moving to GSFC Building 5 for environmental testing.

Epoch2000 provides a good selection of trending and data archival capability. The system utilizes PV Wave to implement this capability.

3.4.5 Wish List for Changes to the Selected Approach

Jim Harrison felt the following items would improve the Epoch 2000 system:

- Designate a single workstation for controlling authorizing commands being sent to the spacecraft. Have commands appear on all displays before being sent to the spacecraft. Currently, the command only shows up on the display sending the command.
- Allow hex commands, bypassing the need to update the database for every command.
- Provide the capability for buffering commands. Current capability calls for each command to be sent as soon as it is entered.
- Faster turn around for database updates.
- Automatic updating and consistency checking of displays, procedures, and database definitions of telemetry points and commands. For example, when a telemetry point name is changed, have all places where that name appears in displays and procedures be updated automatically. The manual way this is currently done is very time consuming.

3.4.6 GDS Functions Not Included in Test Configuration

All requirements will be exercised in the NEAR I&T phase.

3.4.7 Roles of Testing Personnel

A nominal shift during NEAR I&T consisted of:

- Test Conductor who has overall control of the test session
- Test operator that pushes the buttons and enters commands as called out in the test procedure
- Ground System Operator that controls the GSE
- Hardware Specialist is responsible for the spacecraft hardware.

In addition, there may be subsystem specialists present as necessary.

3.4.8 Size and Maturity of the System

Version 0.0 of Epoch 2000 was delivered to APL in January, 1995. Since then, APL has accepted three major upgrades, and numerous patches to their system from ISI. Jim Harrison did not feel the Epoch 2000 was fully capable of supporting I&T when it was delivered.

3.4.9 Issues Related to the Transition to Operations

The transition from I&T to operations is going very well. Operations personnel are using Epoch 2000 for training using a spacecraft simulator provided by ISI. It provides a minimal amount of closed loop simulation capability.

3.5 OS/COMET

3.5.1 Description and Background of I&T System

Open Systems (OS)/COMET is a generic command and control system developed by the NRL and extended and commercialized by Software Technology, Incorporated (STI). OS/COMET was used on Clementine and other missions at NRL and had been selected as the core technology for Motorola's Iridium project, a constellation of over 60 satellites. The product is now marketed as a generic command and control system not limited to the GDS domain.

The Blossom Point facility manages a constellation of satellites using OS/COMET.

We interviewed Dave Schriftman (NRL) at the NRL facility at Blossom Point, Maryland, on January 19, 1996.

3.5.2 I&T System Architecture

OS/COMET simulates network multicast using software. Telemetry values can be broadcast on the bus as "change only". This means that when you join a group, you first request a refresh to receive all the values. Only updates are received after that. This scheme greatly reduces traffic on the bus because, according to Gary Fuller, STI software lead for OS/COMET, telemetry only changes about 15% at any one time. Each node monitors a sequence counter and can request rebroadcast of a packet if the sequence number jumps.

The telemetry and command databases can be easily modified. Rebuilding the database from the ground up takes about 20 minutes. Telemetry points can be added on the fly. To become permanent, these changes must be formally submitted to the database configuration team for processing.

Commands are handled differently for I&T and operations. During I&T, command loads are executed in the GDS and sent to the spacecraft one at a time. During operations, an entire command load is uplinked to the spacecraft, and then executed one at a time onboard. (This is not how commands are processed at GSFC, where command loads are uploaded and executed from onboard memory during both I&T and operations.)

All GSE equipment is controlled through COMET command language (CCL), the OS/COMET equivalent of STOL. (The ability of the tester to command GSE through the GDS is a reflection of the flexibility of OS/COMET and the difference in how the satellite is usually developed for NRL. NRL usually has a strong role in specifying the configuration of the development environment, and require that GSE be developed to conform to the OS/COMET protocol.)

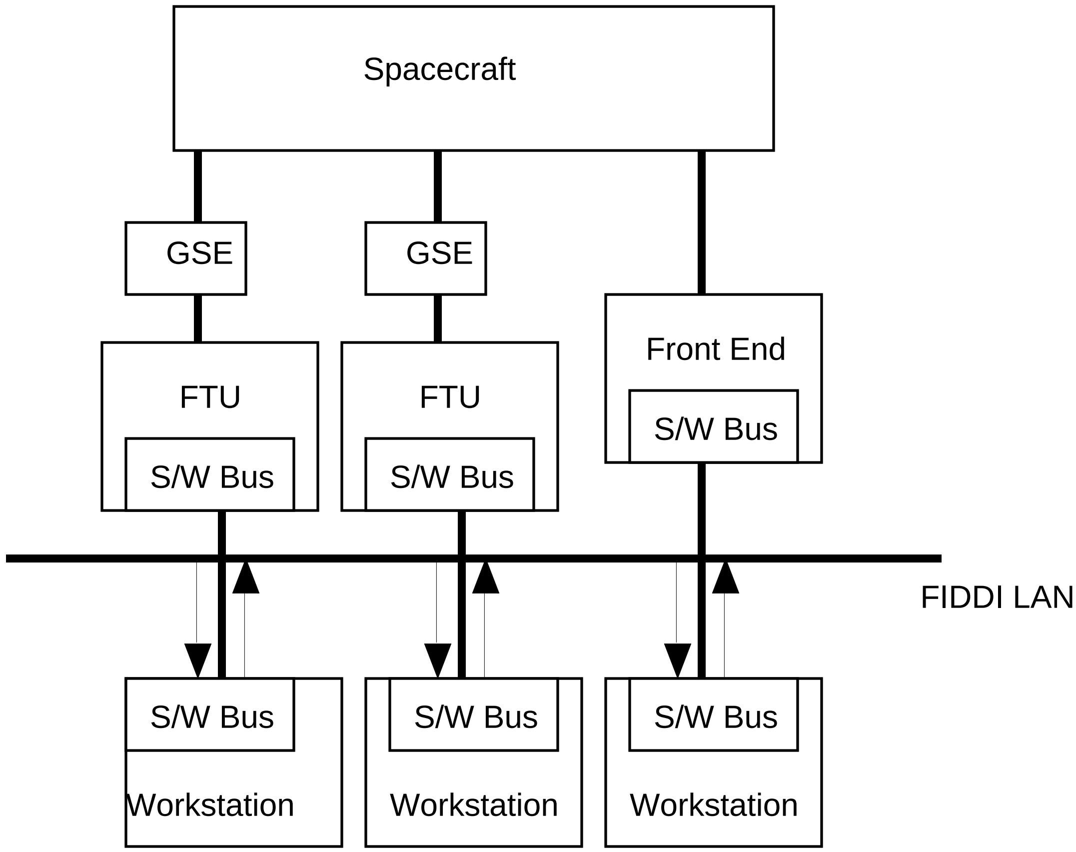

Figure 3-4 OS/COMET Architecture Diagram

3.5.3 Alternatives Considered to Selected Approach

The COMET system was originally developed to specifically support the missions at NRL, so no other alternatives were considered.

3.5.4 System Use in I&T Phases

OS/COMET has a modular design that allows the system to be tailored specifically to the needs of the user. For example, the component developer will use a subset of the system that contains only the functionality necessary to support that activity. This might include the display and telemetry databases, the command and telemetry module, and the ASCII display modules. Interfaces with the unique GSE for a subsystem are hidden behind generic device drivers called Test Functional Units (TFUs). This allowed the component developers to use PCs running Solaris for testing.

Interfaces with operational equipment such as antennas was accomplished by tailoring application specific interfaces (ASI).

3.5.5 **Perceived Strengths and Weaknesses of the OS/COMET System**

The ability of the OS/COMET system to be reconfigured for different users was considered a very important advantage to it's users.

The flexibility to statically redistribute components to different platforms through the software backplane was considered an important advantage of OS/COMET.

Users liked being able to use OS/COMET during component development, I&T, and operations. Many of the displays developed for one phase were used in subsequent phases.

3.5.6 **Wish List for Changes to the Selected Approach**

Gary Fuller thought the addition an inference engine to help monitor and control spacecraft state would be helpful. Complex satellites can take 2-3 hours to put in a known state, which can represent a significant portion of a testers time. The inference engine would assist the tester in putting the spacecraft in the correct state.

3.5.7 **GDS Functions Not Included in Test Configuration**

There are a number of components that run at the Blossom Point facility that are not part of the OS/COMET system.

3.5.8 **Staffing Level**

NOTE

> The staffing levels gathered for this report were not normalized across the various missions that participated in this survey. As a result, the figures cited cannot be used to estimate costs for developing and supporting the missions.

There are about 18 people at the Blossom Point facility that maintain the various ground data systems that operate there. This includes both open and secured systems.

Budgets are usually spent in the following way: one third for science instrument and subsystem development, one third for I&T, and one third for the launcher and launch. (We did not get an estimate of operations costs.)

3.5.9 **Size and Maturity of the System**

STI delivers incremental upgrades to OS/COMET every 6 months. Missions specific capabilities were delivered every six to eight weeks. The testing and delivery of new releases was facilitated by the ability to run in parallel with the existing releases. The new release is run using automated CCL scripts against realtime data at the Blossom Point facility. The philosophy is to make small, incremental deliveries rather than larger ones. The Blossom Point facility release is able to restore a previous version within 3 or 4 minutes.

3.5.10 Issues Related to the Transition to Operations

One of the benefits of using OS/COMET, according to it's users, is that a minimal effort is required to transition from I&T to operations, because the same system is used for each. Features of OS/COMET that facilitated the transition was the centralized telemetry processor.

3.5.12 Miscellaneous

NRL owns the source rights to OS/COMET. GSFC can request a copy of the source code through the Freedom of Information Act. The product is also available through STI for a fee.

4.

4. Requirements For A Spacecraft I&T Ground Data System

4.1 External Factors for Selecting an I&T System

After surveying spacecraft integrators and testers for this study, it is evident that mission managers consider many factors other than the functionality of the candidate systems when deciding which system to procure for spacecraft I&T. The following list describe these "external" factors that are critical in selecting a GDS for spacecraft I&T:

- Size of the mission budget for procuring a GDS.
- Structure of the mission budget categories. If the mission budget has separate budget categories for the spacecraft I&T GDS and the operational GDS, there might be less incentive on the parts of the respective organizations to share a GDS. The structure and budget categories also affect the calculation and tradeoffs of hardware, software, operations and maintenance life cycle costs. For example, a GDS might be relatively inexpensive to buy, but would require relatively highly skilled and expensive personnel to operate. In this case, the life cycle costs for choosing an inexpensive system might be quite different. (Generally speaking, an I&T-based system requires experts to use it - the antithesis of "lights out" operations. Testers tend to be experts on the spacecraft and so generally are of the opinion that less functionality is needed for the operational system.)
- Structure of the mission organization. As with budget categories, the structure of the support organizations may not provide the incentives to motivate personnel to share a single system for bench testing, I&T, and operations. The organization may not allow mission managers to influence the selection of GSE or require that subsystem developers follow a protocol that allows the subsystem GSE to be integrated with the GDS. The structure of the mission organization is also a factor when an advance in technology (expert systems that allow for lights out operations) may have a negative effect on one part of a mission organization.
- Number of spacecraft in the mission. The different economies of scale for a mission with a series of spacecraft and a single-spacecraft mission could affect the choice of GDS.
- Familiarity with a GDS. The selection of a GDS for I&T and/or operations should take into consideration the preferences of the personnel operating it. The mission can avoid additional startup and training costs if it chooses a GDS with which the I&T and operations team know how to operate. As is true for most systems, user's tend to be more effective if they are using a system that they believe in. There is also the influence of the "not invented here" syndrome.

- Functionality of the GDS. This category includes such issues as whether the system supports the telemetry and command protocols and data rates of the mission. There might be prohibitively high costs associated with adding support for a new telemetry protocol the system was not originally designed to handle.
- Complexity of the mission. Complexity is reflected in such areas as:
  - Redundancy. A spacecraft with redundant systems will double the number of commands and telemetry points defined in the data base and exponentially increase the number of modes.
  - Complexity of subsystems (for example, whether the attitude control subsystem is simple or complicated), the number of science instruments, and whether the subsystems might have already been tested for another mission.

  For complex missions, a mission manager could justify the higher up-front costs of a more robust GDS that provides more elaborate support for creating displays and updating command and telemetry definitions. (This is another aspect of the cost factor.)
- Duration of a mission. A mission that will operate for a short time will probably not be able to justify the added costs of a more expensive GDS.
- Modularity of the GDS is particularly important when a single system is going to be used for both I&T and operations.

4.2 Requirements for a Spacecraft I&T Ground Data System

This section describes the requirements for a GDS must provide to support I&T.

4.2.1 Essential Requirements

Based on the survey of I&T systems and the "wish lists" of the survey participants, we believe that an I&T GDS must provide the following essential requirements:

- Command the spacecraft using PDB-defined commands. This will allow testers to enter command mnemonics and have the ground data system translate the mnemonics into the correct bit sequence and send the sequence to the subsystem or spacecraft under test. The users must be able to modify the definitions for these commands.
- Analyze telemetry using displays and reports. This capability can vary from simple text displays to complex graphical displays; text displays are usually preferred for I&T. The GDS must support the telemetry protocol used by the spacecraft. The users must be able to modify the definitions for these telemetry points.
- Run automated procedures (such as the Short Form Function Test (SFFT) and Long Form Function Test (LFFT) described in Section 1.6) using a procedure-oriented language (for example, STOL). I&T personnel rely heavily on procedures to run and re-run the same test or test fragment. For example, the TRMM I&T team has approximately 1,000 STOL procedures as part of the I&T suite.

- Optionally bypass validation checks of commands in order to exercise processing of erroneous commands.
- Be mobile enough that the GDS can be moved to special purpose environmental testing facilities and the launch site, or allow support of such testing remotely.
- Allow users to analyze the sequence of events during a test using events time-stamped when they occur. (Some systems time stamp events when they are received by the Event subsystem, which can cause ambiguity when trying to determine the precise sequence of events.)
- Support the changing test configurations as testing progresses from component testing to I&T and operations. (The phases of testing are described in Section 2 .)
- Provide an archive and playback capability that allows testers to analyze results of a test off-line from the actual test.

4.2.2 Additional Requirements

Although not critical, it is useful for the I&T system to provide the following capabilities:

- Rapid updates to the definition of a telemetry point or command in the PDB. Rapid means a half hour or less. (Rapid updates are important because I&T requires frequent updates to the PDB.) If it takes too long to make the changes, it can cause delays in testing.
- Provide a "ground reference image" of the onboard memory. By dumping and comparing the memory, the tester is able to precisely study the effect of an event on the spacecraft state.
- Distribute subsystem-specific telemetry to subsystem GSE. For CCSDS telemetry this capability means being able to select the AP IDs of the telemetry packets that will be processed by a platform.
- Various subsystem teams to replay and analyze data in parallel. This function requires an archive and playback capability that is robust enough to allow playback during realtime operations.
- Control GSE needed to control the spacecraft during a test with directives from the command line and procedures. An examples of such a directive is a directive to the GSE that stimulates the attitude control subsystem (ACS). Such a directive should be embedded in the test procedure to activate the ACS GSE at the precise moment.
- Display builder with access to the PDB and other displays. This capability allows a user to click on a telemetry mnemonic name and access the database definition and description for that point. It also allows a tester to define a display by editing an existing page. For example, if a spacecraft has redundant A and B sides, the tester should be able to use the definition of a page for Side A mnemonics to be copied and modified slightly to access the same mnemonics for the B side.

- The GDS must be flexible enough to provide the needed capabilities on the platform of choice for component developers and integrators. Based on our survey, the platforms of choice are Macs and PCs.

4.3 Recommendations for Follow-on Activities

The following areas are recommended for further study by the Renaissance Team:

- Use of I&T in box or component testing. This study by and large was limited to the approach to spacecraft I&T at GSFC and related facilities. We should better understand the issues of the component and science instrument developers.
- Take a comprehensive look at the process for developing and integrating a spacecraft. It may result in process changes that would influence the consideration of how the GDS supports either spacecraft I&T, operations, or both.
- Look at the issues of system integration. The GSFC model if for integrating a new spacecraft into an existing and stable network infrastructure. Integrators of missions in the future may need to look at different support tools to help with the integration process.
- Evaluate how automated test equipment might be able to help the testing process.

5.

Glossary

Bench Test	Any test performed in a "stand alone" configuration, whether at a board or a box level. It is so called because it verifies requirements and sets benchmarks for later testing and can usually be run right on a developers workbench.
Calibration	Tests performed to verify a subsystem or instrument response is known, is accurate, and repeatable when subjected to a stimulus for which it was designed to measure.
Functional Test Procedure	An orderly and controlled set of events to validate that a subsystem, instrument or combination of subsystems and/or instruments (i.e. spacecraft functional) is working in accordance to the required specifications. It generally contains a description of the events to be performed, the expected results and any troubleshooting procedures which may be needed, as well as the specific test itself. The test procedure itself is generally written in STOL.
Ground Support Equipment	The equipment, both electrical and mechanical, which is used to support the assembly, integration, test or launch of the spacecraft or parts of the spacecraft payload.
Integration	The process of mechanically and/or electrically assembling any component (mechanical structure, harness, electrical subsystems, instruments or launch vehicle) using a pre-approved integration procedure.
Integration Procedure	A written procedure that details the steps to be performed to integrate components, subsystems, instruments or GSE during I&T. These procedures include mechanical drawings, electrical configuration drawings, breakout box requirements, qualified personnel, etc. to clarify the steps and support needed to perform the task. Two types of integration procedures are required to support I&T activities, Mechanical Integration and Electrical Integration Procedures.
Aliveness Test	A (automated - i.e. STOL) procedure that is used to energize the spacecraft/subsystem/instrument and quickly access the health and safety of the spacecraft/subsystem and verify that it is functioning properly. It is generally limited to the minimum amount of commanding and telemetry verification that is necessary to declare that the item is in working order.
Short Form Functional Test (SFFT) Procedure	A (automated - i.e. STOL) procedure that is used to energize the spacecraft/subsystem/instrument, perform normal operation functional testing and then power down. GSE may be used to excite sensors, actuators, thermometers, instrument detectors, antenna components or other devices as required. The ‘Short Form’ Functional

Test is a cursory test of the subsystem. (This test is often a subset of the 'Long Form' Functional Test). The main purpose of this test is to verify, in a short amount of time, that the subsystem seems to be still alive and working as specified and designed. This test might include: turning on the subsystem; sending the 'key' commands and verifying their execution using telemetry; verifying that 'housekeeping' voltage, current and temperature monitors are operating within their valid limits; operating the subsystem in it's primary operating mode and verifying it is correctly operating in this mode; and turning off the subsystem. Short form functional tests are generally used as a baseline procedure for comparison with future test results.

Long Form Functional Test (LFFT) Procedure A (automated - i.e. STOL) procedure (sometimes known as a comprehensive test) that is used to energize the spacecraft/subsystem/instrument, perform normal, diagnostic, redundant, launch and early orbit and safe hold modes of operation. All possible modes and configurations are tested and all test data is generally archived. These functions include turning on the subsystem; commanding the subsystem and verifying all the proper telemetry responses and mode changes; verifying that all 'housekeeping' voltage, current and temperature monitors are operating within their valid limits; operating the subsystem in an operational type manner for each different mode and verifying that the subsystem responds when operating in each of these modes as specified and designed; and turning off the subsystem. GSE may be used to excite sensors, actuators, thermometers, instrument detectors, antenna components or other devices as required. GSE may be required to perform troubleshooting tests. Long form or comprehensive functional testing may require coordination with other organizations to validate their ground system(s) or data. Long form or comprehensive functional tests are used as a baseline procedure for comparison with future test results.

Test Conductor The person in charge of operation, testing and general health and safety of the spacecraft during all powered up operations. This person executes pre-approved functional tests (STOL Procedures), responds to anomalies and keeps other subsystem and instrument personnel informed of non pre-approved actions (i.e. commands sent to respond to anomalies, commands not included in an approved STOL procedure, status of the spacecraft, actions taken if a procedure or GSE hangs up, crashes, etc.) required during testing.

Test Procedures A written or computer set of instructions defining the steps to be followed to perform the testing of a specific function of a subsystem, instrument or system (spacecraft). It generally includes items such as a narrative of events, expected results, troubleshooting and recovery procedures, required test equipment and qualified personnel required. Several types of test procedures are used during I&T. These include mechanical and electrical integration, functional, specific, aliveness, comprehensive and diagnostic procedures.

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